

Titan's Greenhouse Effect and Climate: Lessons from the Earth's Cooler Cousin

White Paper Submission to the NRC Planetary Science Decadal Survey

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Introduction

In the past few years the public debate regarding climate change of the Earth's atmosphere has gradually shifted from one of causality – an anthropogenic role is now widely accepted – to one of policy. That carbon dioxide (CO₂), methane (CH₄) and other gases produced by plants, animals and industrial activity prevent heat radiation from escaping the planet has been known to science for many decades; and hence their increasing worldwide levels must enhance global warming as inevitably as wearing a sweater will warm a human body. On the other hand, anthropogenic aerosols are known to cool the planet. At this point, absolute scientific consensus ceases. Atmospheric scientists peer into the crystal balls of their computer models and frequently arrive at different answers regarding the fate of the planet 10, 20, 50 and 100 years into the future. Research in this field is passive rather than experimental: scientists cannot try pumping the atmosphere with different pollutants in a thousand different 20-year trials, the way a laboratory test-tube experiment is conducted. Modeling is the best tool that we have for predicting the Earth's future.^[1]

However, our models may be informed by the results available from other natural experiments in atmospheric change that have already been conducted: namely the other 'terrestrial' worlds of the solar system, traditionally the inner planets Mercury, Venus and Mars. These latter two worlds exhibit present-day atmospheres, although vastly different from our own; being composed mostly of CO₂ rather than nitrogen (N₂) like the Earth's, and moreover being much more massive (Venus) and less massive (Mars) than our world's. The surface of Venus experiences the same atmospheric pressure as the water pressure at a depth of nearly 1 km in our seas, while the surface of Mars corresponds to the pressure at 100,000 feet (30 km) altitude above the Earth. However, another atmospheric analog is arguably much more Earth-like: Titan, the largest moon of Saturn.

Titan's Earth-like credentials have been recognized for some time, beginning with the discovery of its atmosphere in 1907, and greatly enhanced with the evidence obtained during the Voyager 1 encounter in 1980 that it is mostly composed of N₂, with a surface pressure just 40% larger than terrestrial (equivalent to 13 ft or 4m depth in the ocean). Following these measurements, calculations showed that Titan's atmosphere, like that of the Earth, Mars and Venus, causes 'greenhouse' warming of the surface, discussed in more detail below. More recently, the NASA Cassini mission^[2] that arrived in Saturnian orbit in 2004, and the ESA Huygens Titan lander of 2005^[3], have been returning a flood of new data regarding this intriguing world. For the first time we are now building a detailed picture of weather in the lower atmosphere, where condensable methane takes on the role played by water in the Earth's atmosphere, leading to methane rainfall, rivers and lakes (Fig. 1).

In this white paper we examine the atmospheric parallels between the Earth and Titan, including the possibilities for dramatic climate change, and argue that by investing in scientific study of Earth's 'distant cousin', we may hope to gain a greater understanding and insight into the atmospheric equilibrium of our own planet. Extending the duration of the Cassini spacecraft mission during the next decade will provide part of the needed picture, but in addition, we urge planning for a future new mission focused on Titan.

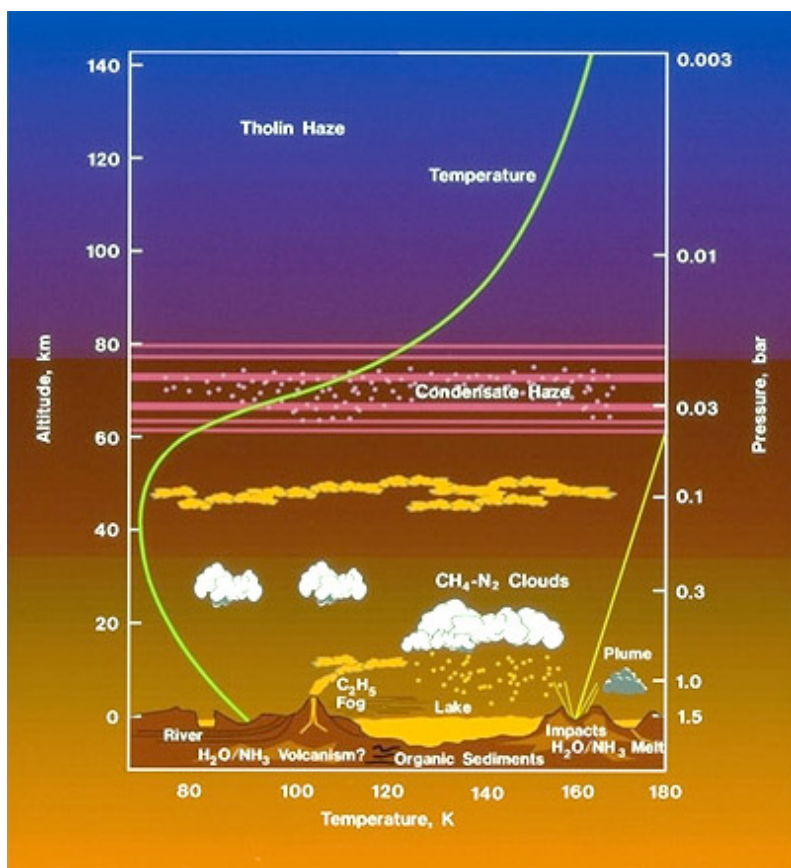


Figure 1: schematic diagram of Titan's atmosphere showing levels of cloud and haze formation, and surface processes. Credit: ESA

The Greenhouse Effect

The Earth's 'greenhouse effect' was first noted by Joseph Fourier in 1824 and investigated quantitatively by Svante Arrhenius in 1896. The term refers the phenomenon whereby gases in the Earth's atmosphere (principally the triatomic molecules H_2O and CO_2) are much more transparent to incoming visible sunlight than to the infrared re-radiation from the surface. This causes the mean temperatures in the lower atmosphere and surface to be elevated relative to an airless world in equilibrium with solar flux: by about 30 K for the surface. Similarly, much greater and lesser greenhouse conditions are seen on Venus (500 K) and Mars (5 K) due to their CO_2 atmospheres. On the Earth, an

additional feedback loop exists between the condensable species H_2O , which is the main greenhouse gas, and the second most important CO_2 , whose concentration is not limited by saturation. This occurs due to the steep dependence of the saturation vapor pressure (SVP) on temperature: small rises in atmospheric temperature due to increased CO_2 levels (e. g. by pollution) are amplified by the greater amounts of water vapor that subsequently are retained in the atmosphere.^[4]

On Titan, a parallel situation to the terrestrial planets exists. The atmosphere is dominated by N_2 (95-98.6%), with significant amounts of CH_4 (5-1.4%) and H_2 (0.1%)^[5]. The action of solar UV photons and energetic particles in the upper atmosphere causes photolysis of methane and nitrogen, leading to diverse organic compounds: ethane (C_2H_6), HCN and higher organics, including aromatics such as benzene (C_6H_6), and ultimately macromolecules and organic haze particles^[6]. The infrared opacity is mainly due to collision-induced absorption of $\text{N}_2\text{-N}_2$, $\text{N}_2\text{-H}_2$ and especially $\text{CH}_4\text{-N}_2$ pairs: a significant departure from the triatomic absorption that causes greenhouse warming of the inner planets^[4]. However the effect is substantial: Titan's retains 90% of surface radiation, intermediate between the prodigious Venus (99.9%), and the Earth (60%), raising its surface temperature from 82 K to 94 K^[7]. A feedback loop also exists, whereby increases in H_2 raise the infrared opacity and thereby the greenhouse warming, causing more CH_4 to be retained in the atmosphere, still greater opacity, and further warming.

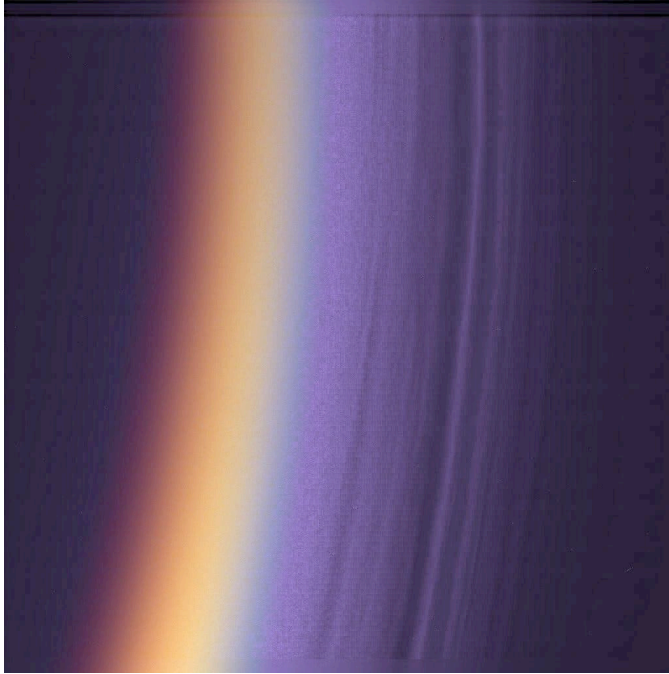


Figure 2: Cassini Narrow-Angle Camera (NAC) image (PIA06160) of Titan's limb at 10S latitude, showing multiple (at least 12) haze layers. Credit: NASA/JPL/SSI

In fact, the surface would be even warmer still (105 K) if it were not for a competing radiation process: the so-called 'antigreenhouse effect'. As the name implies, this phenomenon is the reverse of the greenhouse effect: an atmospheric component that absorbs at visible wavelengths but is transparent in the thermal infrared. On Titan, the main antigreenhouse effect is due to the ubiquitous haze layers (Fig. 2) that obscure the surface at most visible wavelengths, with an additional component due to the near-infrared absorption bands of CH_4 . On Earth, O_3 currently contributes a small antigreenhouse cooling, but in the recent past volcanic eruptions have measurably cooled the planet, and historically large impacts such as the proposed K-T event^[8] must have caused far greater global temperature drops.

Titan's haze is therefore a major component of the atmospheric energy balance, and so chemistry as well as physical processes must be considered in this complex system.

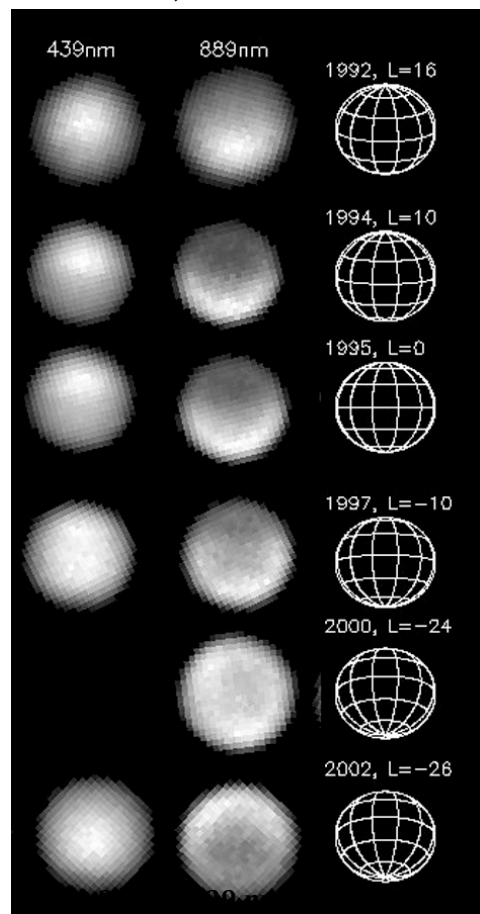
Summary: *Titan's atmosphere exhibits a greenhouse effect similar to the Earth's, including feedback loops. Studying other greenhouse atmospheres in our solar system is likely to inform our understanding of our own atmosphere.*

Seasonal Change

Titan's axial tilt is nearly zero relative to its orbit around Saturn, however, by orbiting in Saturn's equatorial plane it inherits Saturn's tilt (obliquity) of 26.7° , quite similar to that of the Earth (23.4°). Therefore Titan experiences seasons, although the cycle is 29.6 Earth years in length due to Saturn's orbital period. Imaging of Titan's disk over a full year, beginning with Voyager 1 in 1980 and continuing with ground-based observations^[9], through to the present era with Cassini, have revealed the dramatic effects of seasonal change on the moon's appearance. Fig. 3^[10] shows a portion of that history. In the northern fall (1992) Titan is 'smiling' a bright, up-turned arc in the southern hemisphere at red wavelengths (889 nm), which reverses to a 'frowning' arc in the north in 2002 (northern mid-winter). The opposite is true in blue wavelengths, with the north brighter in 1992 and the south in 2002. What is going on?

We now understand that this variation is caused by the stratospheric circulation. In southern summer, models^[11] predict a single cell with warm air rising in the southern stratosphere and sinking in the north. At equinoxes this changes to a two-cell system, with air rising at the equator and sinking in the polar regions. By northern summer the single cell circulation reappears, but directed north to south. The hazes, which are reddish in color, are dragged from the summer to the winter hemisphere, causing the haziest hemisphere to appear bright in red light and dark in blue, which is sensitive to CH₄ deeper in the atmosphere. There is evidently some delay in the reaction of the atmosphere to the insolation, as in 1995 at equinox the two hemispheres are still quite different, and did not reach parity until some five years later near northern mid-winter as defined by solar elevation.

The seasons affect more than just the haze however: Cassini, at a similar Titan season to Voyager, has detected huge enhancements in the stratospheric abundances of trace gas species above 50°N compared to the low-latitudes, especially in the nitriles (-CN molecules) and alkynes (-C≡C)^[12]. These gases are produced high in the mesosphere and many have short lifetimes, so their abundance normally drops sharply at lower altitudes. The reason for the large enhancements is again probably due to dynamical effects. During northern winter, the single-cell circulation implies downward air currents (advection) in the north, which brings down enriched air from the mesosphere into the lower stratosphere. The northern stratospheric air is also confined, being dynamically isolated in a winter polar vortex^[13] that bears comparison to the Antarctic winter polar vortex on Earth, an important site of ozone destruction.



(889 nm, left) image series of Titan showing seasonal change in the haze, from northern fall (1992) to mid-winter (2002). Credit: R. Lorenz/STScI

Other seasonal effects are apparent too: a hemispheric asymmetry in surface temperature^[14], with the north colder than the south; a giant cloud over the northern pole thought to be condensed ethane^[15]; and surface lakes, which appear much more prevalent in the north than the south at present^[16]. This may be an indicator of greater rainfall in the north seasonally, although some permanent hemispheric differences in the lakes (prevalence and extent) also appear likely based on present sampling.

Titan has differences as well as similarities to the Earth that may be equally informative: Titan's slower rotation provides an opportunity to study seasonal variations in equator-to-pole energy transport under a very different dynamical regime than that of the Earth's atmosphere. Understanding the general circulation under these conditions could build upon our capability to predict changes that may occur in atmospheric and

oceanic energy and moisture transport under conditions of severe climate change on Earth over the next one or two centuries.

Summary: Titan has a ‘methanological’ weather cycle of clouds, rainfall and evaporation that parallels the ‘hydrological’ cycle of the Earth; a seasonal variation of haze coverage and chemical composition; and dynamical effects that mirror important processes in the Earth’s atmosphere. Understanding Titan’s climate is a useful test of our theoretical understanding of the terrestrial atmospheric dynamics, physics and chemistry.

The Fate of The Atmosphere

Titan’s upper atmosphere functions as a vast chemical factory, consuming the raw ingredients CH_4 and N_2 , and converting these via multifarious steps and pathways to heavy hydrocarbons, nitriles and haze that ultimately coagulate or condense, and are permanently removed (Fig. 4). Indeed, CH_4 is currently being photolyzed at a rate that is limited only by the solar flux^[17], and the entire current inventory will be expended in just $\sim 10^7$ years^[6] – a cosmic instant – unless it is being somehow replenished. Unless we are observing Titan at some very unusual moment in its history when the last of its CH_4 is vanishing, then resupply must be occurring and there is much debate at present as to whether this is occurring continuously or episodically. Theories center on out-gassing^[18] or cryovolcanic^[19,20] eruptions from the interior, where CH_4 is likely stored in a water matrix (clathrate) along with dissolved ammonia that has historically supplied the atmospheric nitrogen.

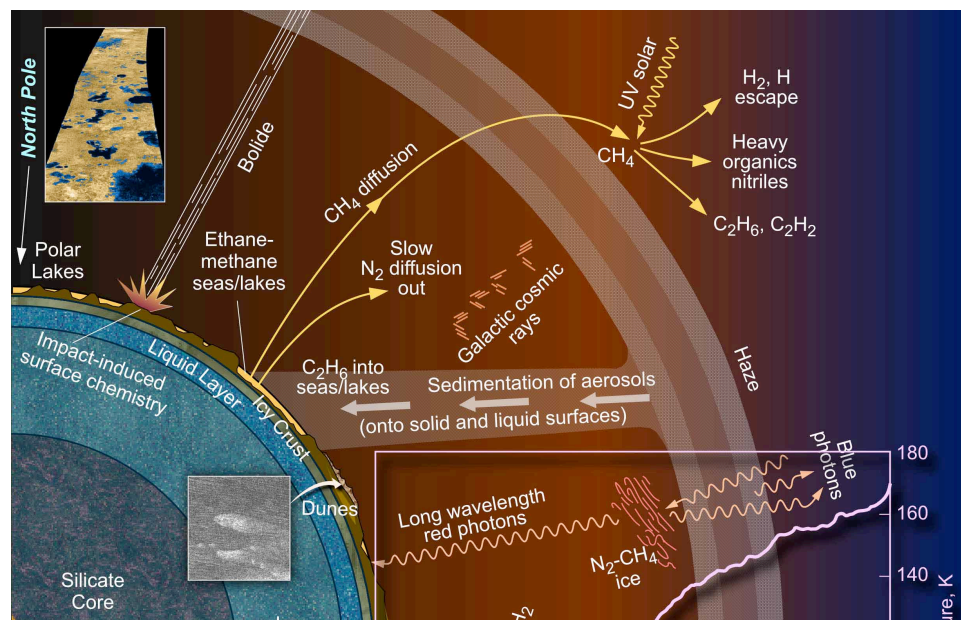


Figure 4: schematic summary of Titan atmospheric and surface processes. See text for details. Credit: Titan-Saturn System Mission Final Report, based on an original figure by Lunine, 1993.

However, sooner or later Titan’s methane supply will run out, and once the atmospheric methane starts to decrease, then the main CH_4 - N_2 greenhouse effect will also quickly diminish, and the surface temperature will fall. Haze particles drop out rapidly once they cease to be created (~ 1000 years) and the antighreenhouse effect will also vanish, while the present warm stratosphere (~ 180 K) will cool to 60 K. H_2 , which is a product of CH_4 photolysis, will escape with a timescale of ~ 2 Myr, further reducing the greenhouse effect. In this cold atmosphere, condensation of N_2 sets in, reducing the final component of greenhouse opacity (N_2 - N_2 collisions at

wavelengths longer than 50 microns), and causing further surface cooling. The process finally stabilizes, as the thermal emission peak also moves to longer wavelengths, and encounters the greater opacity due to the nitrogen collisions^[21].

Does this picture relate to our understanding of the Earth's future evolution? Titan is in a state of rapid loss of volatiles, a state that apparently existed on Mars and Venus in the past, for different reasons. On Venus, a runaway greenhouse effect led to destruction of H₂O and loss of H₂, while on Mars the shutdown of the planet's internal dynamo and consequent loss of protective magnetic field has been implicated in the destruction of the atmosphere. In the distant future (several billion years), increasing solar brightness may eventually push the Earth towards a Venus-like state. The warming atmosphere will increase the cold-trap temperature at the tropopause, allowing H₂O vapor to reach the stratosphere where it is irreversibly photolyzed, as H₂ escapes to space. CO₂ levels will rise, and the Earth will heat up and dry out: an unpleasant prospect that will become inexorable in the next few billion years^[22]. Anthropogenic effects on climate are unlikely to produce such a radical state in the near future, nevertheless the feedback loops are incompletely understood, and therefore we are obliged to learn as much as we can about possible future extreme states of the Earth, by studying the fate of other less-fortunate worlds.

***Summary:** Titan is a case study in climate change with many unresolved questions, including the present stability of the atmosphere. By our researches into the atmospheric evolution of Titan and the terrestrial planets we can attain a better appreciation of how the Earth may undergo periodic and permanent, natural and anthropogenic changes in climate.*

Studying Titan

In the next decade, we identify 3 primary means of studying climate effects on Titan:

- **Cassini-Huygens:** the Cassini spacecraft, in Saturn orbit since 2004, continues to function extremely well with all instruments still operating at or near full health. Now into its two-year extended mission (7/2008-9/2010) designed to include the northern vernal equinox (8/2009), the mission has submitted a request for a 7-year extension to enable observations to continue through to the northern summer solstice (2017), allowing a thorough investigation of seasonal change during 1½ Titan seasons. The ongoing data collection by Cassini is complemented by the one-time dataset from the Huygens lander, which is the subject of ongoing analysis.
- **Remote telescopic observations:** including ground-based facilities using adaptive optics for imaging, high-resolution spectroscopy, and other photometric and spectrometric monitoring; the Stratospheric Observatory For Infrared Astronomy (SOFIA), when operational (~2014); and space-based facilities, primarily the Webb Space telescope when operational (~2014).
- **A future Titan-focused spacecraft mission:** although any future Titan spacecraft mission will not return data during the next decade covered by this survey, planning for such a mission must take place, and building and launching the spacecraft during this window is possible. ^[17,23]

Recommendations

We recommend that the following steps be taken by the NRC Decadal Survey for Planetary Science, to allow for critical research to continue into the subject of Titan's climatology, and comparative planetology with terrestrial planets including the Earth:

- Endorse the strong positive findings of the recent Senior Review of the Cassini Solstice Mission, and recommend that continued funding is provided for this highly successful mission.
- Urge in the Decadal Survey that a Titan-focused mission be given very high priority for near-term development and launch. Given the long flight time to Titan, development must begin soon to avoid a large gap between the end of the Cassini mission and the first data return from a Titan follow-on mission.
- Recommend continued funding for a strong ground-based (including Keck, Gemini, IRTF, ALMA facilities), airborne and space-based observational campaign for continuous, long-term Titan monitoring, to complement dedicated outer solar system missions.
- Support continued funding for applicable NASA R&A programs (including CDAP, OPR, PAST, PATM, PG&G) and the NSF Planetary Astronomy Program; and funding for laboratory experiments, modeling and theoretical calculations that provide critical input in the analysis and interpretation of observations.
- Propose that a dedicated NASA outer planetary mission flagship program be initiated, analogous to the Mars and lunar programs, to encompass the continued operations of Cassini, and follow-on flagship missions.

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